Subgrid-Scale Parameterization in 3-D Models: The Role of Turbulent Mixing

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LONG-TERM GOALS

The long-term goal of this effort is to help improve turbulent mixing parameterization in 3-D numerical ocean circulation models used for studying the oceans, and in operational centers, for nowcasting/forecasting the oceanic state.

OBJECTIVES

The principal objective of this research is to help improve second moment closure (SCM) based ocean mixed layer (OML) models that are in current (and potential future) use in Navy community and operational ocean circulation models.

APPROACH

Extensive research over the past three decades has established second moment closure as a reasonable compromise between resource-intensive techniques such as large eddy simulations (LES) and simple bulk mixed layer models (for example, *Large et al.,* 1994). The SMC approach in its most practical form reduces to a two-equation model of turbulence, with prognostic equations for the turbulent kinetic energy (TKE) and the turbulence length scale (TLS), and algebraic expressions for the mixing coefficients (*Mellor and Yamada*, 1982; *Galperin et al.,* 1988; *Kantha and Clayson* 1994, 2000). These so-called algebraic stress closure models have become the mainstay of the US Navy operational ocean and atmosphere forecast models, for example the Shallow Water Analysis and Forecast System (SWAFS) run routinely at NAVOCEANO and Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) run at FNMOC, as well as many civilian operational (NOAA NCEP) and research (NCAR WRF) forecast systems.

However, three decades of research and over a decade of operational use have exposed some shortcomings of the current SMC-based OML models. For example, the popular Mellor-Yamada (MY) OML models in Navy operational use, have a tendency to under predict mixing and hence overestimate upper layer currents and SST. The most glaring conceptual weakness is the one related to the prescription of the turbulence length scale. MY models use an *ad-hoc* wall correction to their TLS equation (Mellor and Yamada 1982), whereas the k-ε (TKE and its dissipation rate) model used extensively by the European community (for example, *Rodi,* 1987) exhibits disturbing singular behavior in parts of the parameter space (*Burchard* and *Deleersnijder,* 2001). Another drawback is the local nature of the closure that does not work well under free convection conditions. Yet another one is ignoring the very important influence of surface gravity waves on mixing in the upper ocean. None of the Navy community ocean models such as ROMS/TOMS, NCOM and HYCOM incorporate completely surface wave effects; neither do they account for non-local effects under convection.

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Observational data to compare with turbulence models are scarce. Microstructure measurements have not become a routine staple of oceanographic measurements as CTD casts have been for decades. This has led us to make microstructure measurements during NURC/NRL 2006 DART cruises in the Adriatic Sea. We have taken part in the DART 06A and 06B cruises in March and August of this year and collected turbulence data using a microstructure profiler. See *Prandke* (2005) and *Prandke et al.* (2000) for details of the microstructure profiler used.

WORK COMPLETED

We have processed and analyzed the microstructure data collected during the DART cruises (see *Carniel et al.* 2006 for details) and made comparisons with modeled dissipation rate and diffusivity from ROMS/TOMS model. Figure 1 shows an example of the measurements made during the March 2006 DART06A cruise. Layered density structure most likely due to double-diffusive convection resulting from cold fresh water masses over warm salty ones can be seen in the buoyancy frequency and χ profiles.

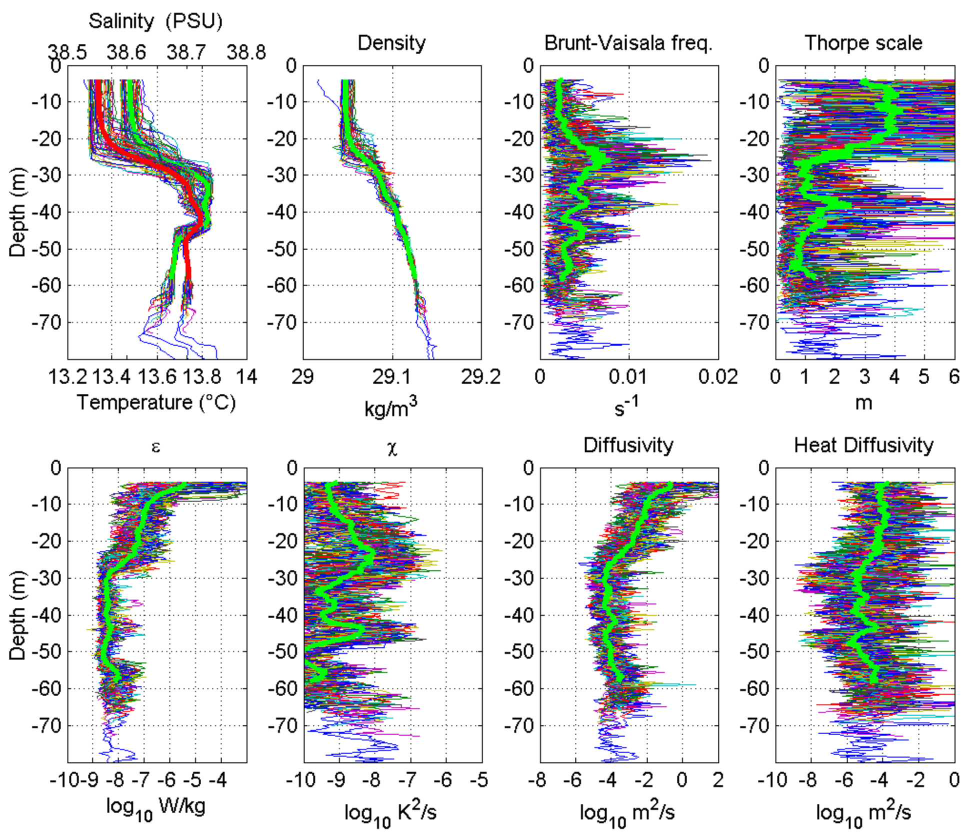

Figure 1. Profiles of temperature (°C) and salinity (PSU), density (kg m-3), buoyancy frequency (s-1), and the Thorpe scale (top panels); TKE dissipation rate (W kg-1), temperature variance dissipation rate (K2 s-1), eddy diffusivity K (m2s-1) and heat diffusivity Kh (m2s-1) (bottom panels) measured in the Gulf of Manfredonia. A total of 43 casts were made over 2.5 hr centered spanning the midnight of March 23rd/24th. The thick green (red for salinity) line denotes the corresponding average value.

Figure 2 shows an example of the measurements made during the August 2006 DART 06B cruise under conditions of strong winds and weak nocturnal cooling. Strong summer-time pycnocline and vigorous mixing in the upper layers can be clearly seen. Note the large Thorpe scales in the mixed layer.

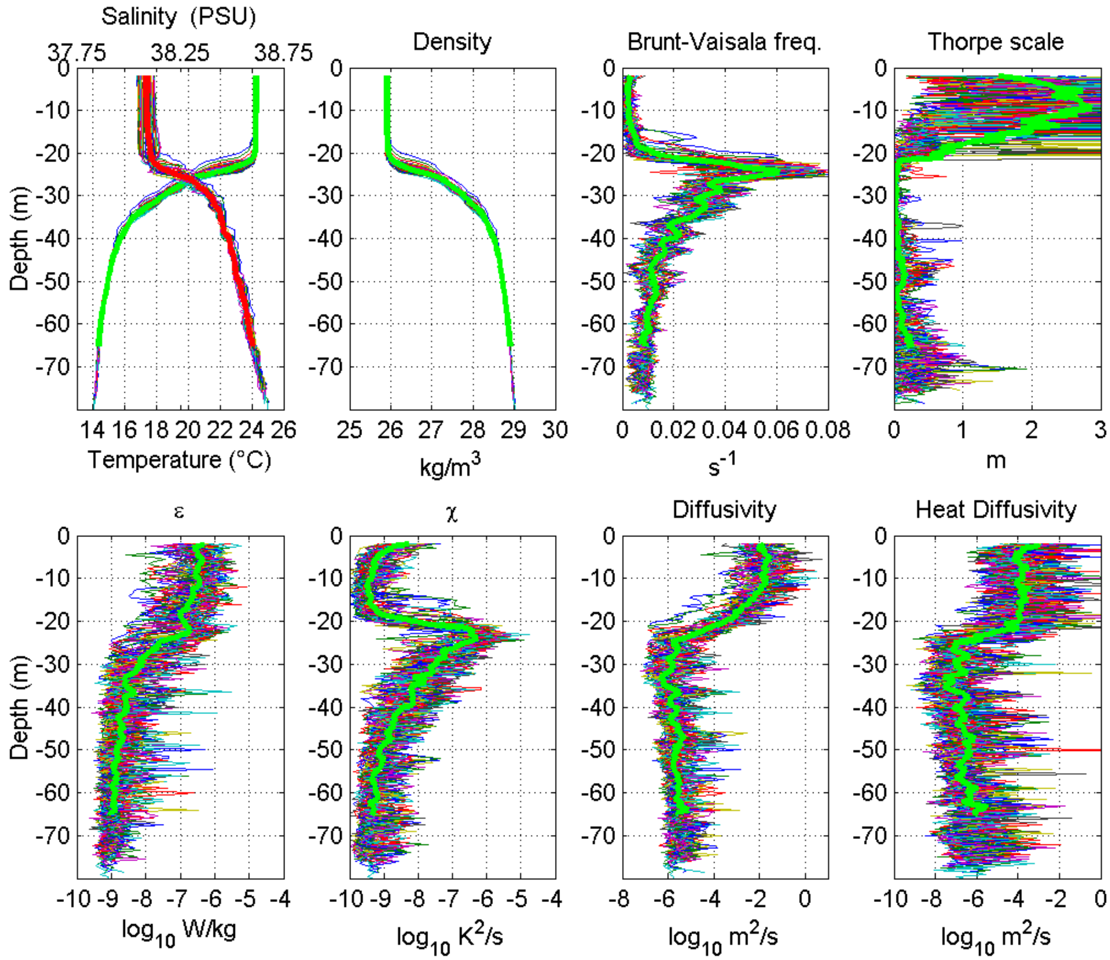

Figure 2. Profiles of temperature (°C) and salinity (PSU), density (kg m-3), buoyancy frequency (s-1), and the Thorpe scale (top panels); TKE dissipation rate (W kg-1), temperature variance dissipation rate (K2 s-1), eddy diffusivity K (m2s-1) and heat diffusivity Kh (m2s-1) (bottom panels) measured in the Gulf of Manfredonia. A total of 40 casts were made over 2.5 hr centered spanning the midnight of August 22nd/23rd under strong winds and weak nocturnal cooling. The thick green (red for salinity) line denotes the corresponding average value.

RESULTS

A destabilizing buoyancy flux at the ocean surface leads to convective mixing in the water column. Under pure convection, the TKE dissipation rate ε must simply scale as the surface buoyancy flux *Jb0*. It has been the practice hitherto, following *Shay and Gregg* (1984, 1986), *Lombardo and Gregg* (1989) and *Brainerd and Gregg* (1993 a, b) to assume that the dissipation rate $\varepsilon \sim cJ_{b0}$ is constant in the entire mixed layer under pure convection (e.g. *Peters et al.* 1988, 2006). The value of the constant is taken as ~0.58 following *Lombardo and Gregg* (1989). However, *Carniel et al.* (2006) show that a more reasonable value for c to be 0.39. Therefore, in the convective mixed layer

$$\begin{aligned} \varepsilon_c &= J_{b0} && z = 0 \\ &= 0.39 J_{b0} && 0.1D \le z \le 0.9D \\ &= 0 && z \ge D. \end{aligned} \tag{1}$$

In the regions $0 < z < 0.1D$ and $0.9D < z < D$, ε goes linearly from 0 to 0.39 J_{b0} and from 0.39 J_{b0} to 0, respectively. On the other hand, when the turbulence in the mixed layer is mechanically driven, by the wind stress, the law of the wall demands that the dissipation rate near the surface follow the relationship $\varepsilon = u_*^3/(\kappa z)$, where κ is the von Karman constant, u^* is the friction velocity and z is the distance from the surface. This similarity relationship should hold in the upper few meters near the surface if we ignore the wave effects on ε scaling. The falling microstructure probe did not allow us to make measurements in the upper 2-3 m, where the influence of surface waves on the TKE dissipation rate is most prominent. *Carniel et al.* (2006) show that in the wind stress-driven mixed layer,

$$\begin{aligned} \varepsilon_s &= u_*^3/(\kappa \mathrm{z}) && 0 \le z \le 0.3D \\ &= 3.33 u_*^3/(\kappa D) && 0.3D < z \le D \\ &= 0 && z > D. \end{aligned} \tag{2}$$

Below the mixed layer and in the interior of the water column, mixing is episodic and internal wave field-driven. The relevant length scale is the Ozmidov length scale $L_O = \sqrt{\dfrac{\varepsilon}{N^3}}$. If we further assume that the Thorpe scale *LT* (*Thorpe* 1977) is proportional to the Ozmidov scale *LO* (e.g., *Dillon*, 1982; *Stansfield et al*., 2001), the dissipation rate can be taken to be $\varepsilon_i = 0.03 L_T^2 N^3$, where the proportionality constant has been determined by the best fit to values appropriate to the observed background dissipation rate deep in the water column (depth ~ 60-80m).

When the turbulence is generated by both the momentum flux and a destabilizing buoyancy flux, the TKE dissipation rate ε in the mixed layer can be taken to be the sum of the rates due to shear-driven and buoyancy-driven turbulence. Therefore

$$\begin{aligned} \varepsilon &= \varepsilon_c + \varepsilon_s && z \le D \\ &= \varepsilon_i && z > D \end{aligned} \tag{3}$$

Figure 3 shows the TKE dissipation rate profiles plotted along with the profile indicated by Eq. (3) for three observation periods (OP) at B90 station: B90-2, B90-3 and B90-4. The conventional scaling (*Lombardo and Gregg* 1989; *Brainerd and Gregg* 1993 a, b; *Stips et al*. 2002)

$$\begin{aligned} &\varepsilon_c = 0.58 J_{b0};\ \varepsilon_s = 1.76 u_*^3/(\kappa z) \\ &\varepsilon = \varepsilon_c + \varepsilon_s \end{aligned} \tag{4}$$

is also shown. It can be seen that Eq. (3) is a better depiction of the dissipation rates in the deep than the traditional formulation (Eq. 4), which has little validity below the upper mixed layer and hence should not be applied except in the mixed layer. In the mixed layer itself, the difference between the two formulations is small, although Eq. (3) is better justified from first principles. The disagreement between the theoretical formulations and the observed values is undoubtedly due to inaccuracies in inferring *Jb0* and *u** from bulk formulae.

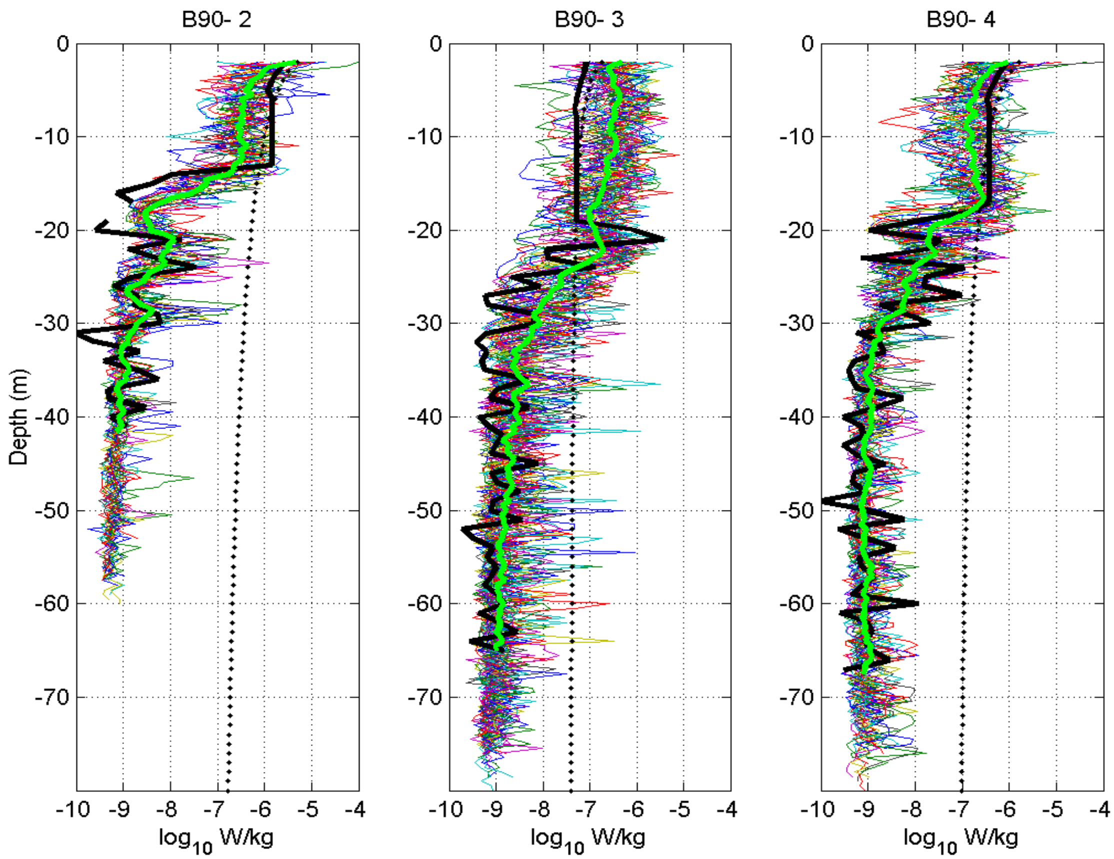

Figure 3. Observed dissipation rates observed at Station B90 compared with theoretical scaling for OPs B90-2, B90-3 and B90-4: thick black line (Eq. 3), black dotted line (Eq. 4), and green line (observational mean).

IMPACT/APPLICATIONS

Accurate depiction of many quantities of interest to worldwide naval operations, such as the upper layer temperature and currents, requires accurate simulation of turbulent mixing in the water column and accurate tidal forcing. Operationally, this contributes to better counter mine warfare capabilities through better and more accurate tracking of drifting objects such as floating mines. Other drifting materials such as spilled oil are also better tracked and counter measures made more effective. Other applications include search and rescue. Turbulence data collected under this project can help assess turbulence parameterization in OML models.

RELATED PROJECTS

1. Astronomical Tides and Turbulent Mixing in ROMS/TOMS (PI - L. Kantha) – N00014-06-1-0287. Started February 2006.

2. Improving the Skill of Ocean Mixed Layer Models (PI - L. Kantha) – N00014-05-1-0759. Ended June 2006.

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1. Carniel, S., L. Kantha, H. Prandke, M. Rixen, and J. Book (2006) Turbulence Measurements Across a Coastal Front in the Southern Adriatic Sea during Spring 2006. (under preparation).

2. Carniel, S., L. Kantha, H. Prandke, J. Chiggiato, and M. Sclavo (2006) Turbulence in the Upper Layers of the Southern Adriatic Sea Under Various Meteorological Conditions During Summer 2006. *J. Geophys. Res.* (submitted).